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On The Valuation of Infiltration towards Meeting Residential Ventilation Needs

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ABSTRACT

The purpose of ventilation is dilute or remove indoor contaminants that an occupant is exposed to. It can be provided by mechanical or natural means. In most homes, especially existing homes, infiltration provides the dominant fraction of the ventilation. As we seek to provide acceptable indoor air quality at minimum energy cost, it is important to neither over-ventilate nor under-ventilate. Thus, it becomes critically important to correctly evaluate the contribution infiltration makes to both energy consumption and equivalent ventilation. ASHRAE Standards including standards 62, 119, and 136 have all considered the contribution of infiltration in various ways, using methods and data from 20 years ago.

Keywords: Infiltration Mechanical Ventilation, Ventilation Effectiveness, Residential Ventilation

Introduction

Infiltration, adventitious or incidental air leakage through building envelopes, is a common phenomenon that affects both indoor air quality and building energy consumption. Infiltration can contribute significantly to the overall heating or cooling load of a building, but the magnitude of the effect depends on a host of factors, including environmental conditions, building design and operation, and construction quality. Typically infiltration accounts for one-third to one-half of the space conditioning load of a home.

In addition to increasing the conditioning load of a building, infiltration can bring unwanted constituents into the building or into the building envelope and cause building failures. For example, infiltration of hot, humid air in an air conditioned building in the summer (or exfiltration of indoor air in a heated building in the winter) can cause condensation in the building envelope leading to potential structural failure and mold growth. For these reasons reducing infiltration would be desirable.

Infiltration, however, serves a vital purpose in most existing homes: it is the dominant mechanism for providing ventilation. The purpose of ventilation is to provide fresh (or at least outdoor) air for comfort and to ensure healthy indoor air quality by diluting contaminants. Historically, people have ventilated buildings to provide source control for both combustion products and objectionable odors (Sherman 2004). Currently, a wide range of ventilation technologies is available to provide ventilation in dwellings including both mechanical systems and more sustainable technologies. Most of the existing housing stock in the U.S. uses infiltration combined with window opening to provide ventilation. Sometimes this results in over-ventilation with subsequent energy loss or under-ventilation and poor indoor air quality.

Recent residential construction methods have created tighter, more energy-saving building envelopes that create a potential for under-ventilation (Sherman and Dickerhoff 1994)), Sherman and Matson 2002). McWilliams and Sherman (2005) have reviewed such standards and related factors. Infiltration rates in new homes average a half to a quarter of the rates in existing stock. As a result, new homes often need mechanical ventilation systems to meet current ventilation standards.

Unless buildings are built fantastically tight and fully mechanically ventilated, infiltration is always going to contribute towards ventilation. Ignoring that contribution can lead to over-ventilation and unnecessary energy expense, over-estimating of that contribution can lead to poor indoor air quality. This report uses simulation methods to help determine how infiltration can and should be properly valued in the context of residential ventilation.

ASHRAE Standards

A key motivation for understanding infiltration's role in ventilation is when trying to apply energy and/or indoor air quality standards. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) is the key organization and the only one to have American National Standards on residential ventilation and infiltration. The three key standards are Standards 62.2, 119 and 136.

Standard 62.2 (2007) sets requirements for residential ventilation and acceptable indoor air quality. There are source control requirements and there are minimum ventilation requirements. The standard appears to be mostly about mechanical ventilation systems, but has a default infiltration credit and allows mechanical ventilation rates to be reduce based on an infiltration credit measured using ASHRAE Standard 136.

Standard 136 (1993) uses pre-calculated weather factors and the air tightness measured using normalized leakage (of Standard 119) to estimate the impact that infiltration would have on indoor air quality and thus determine its equivalent ventilation. This concept will be described in more detail in later sections.

Standard 119 (1988) defines how to measure normalized leakage and also specifies tightness levels based on energy conservation concerns. Herein, we are only concerned with the measurement aspect of 119, which defines the metric (Normalized Leakage) that is used in the ASHRAE Standards.

We will look at the impacts of infiltration towards providing acceptable indoor air quality and examine the need to change these standards, particularly standard 136, accordingly.

Background

To understand the contribution of infiltration we review the role of air tightness and weather in driving infiltration and the role ventilation has in providing acceptable indoor air quality. Infiltration is a time-varying phenomenon that affects ventilation through leaks in the building envelope induced by changes in the pressure field around the building. The purpose of the ventilation is to reduce contaminant exposures by diluting the indoor sources. Ventilation standards implicitly assume constant ventilation (and often a constant source). To determine the impact that a time varying situation will have that would be equivalent to a time invariant one requires that we understand the relationship to the quantity is of interest—IAQ and that requires some modeling. As we will see, the Sherman-Wilson approach to effective ventilation can be used to define infiltration efficiency. It does so by determining the steady-state ventilation that would provide the same dilution as the actually occurring infiltration.

Air tightness

"Air Tightness" is the property of building envelopes most important to understanding ventilation. It is quantified in a variety of ways all of which typically go under the label of "air leakage". Air tightness is important from a variety of perspectives, but most of them relate to the fact that air tightness is the fundamental building property that impacts infiltration. There are a variety of definitions of infiltration, but fundamentally infiltration is the movement of air through leaks, cracks, or other adventitious openings in the building envelope. The modeling of infiltration (and thus ventilation) requires a measure of air tightness as a starting point. More extensive information on air tightness can be found in Sherman and Chan (2003), who review the state of the art. This information is also part of a broader state of the art review on ventilation compiled by Santamouris and Wouters (2005).

Sherman and Chan (2003) also discuss the topic of metrics, reference pressures and one versus two parameter descriptions in some detail. There are various metrics one could use other than Normalized Leakage. For example, air flow at a fixed pressure is the easiest one to measure but suffers from accuracy issues and does not account for house size in anyway. Similarly, leakage per unit exposed surface area is a good estimate of the porosity of the envelope, but does not scale correctly for either energy purposes or indoor air quality purposes.

We have chosen to use the metric of Normalized Leakage (NL) as defined by ASHRAE Standard 119 (1988, 2005) as our primary metric to describe air tightness of houses because it removes the influence of house size and height, because it scales better with house size and because it is used in the other ASHRAE standards. The metric is as follows:

1. $$NL = 1000 \cdot \frac{ELA}{FloorArea} \cdot \left(N_{story}\right)^{0.3}$$

Where NL is the normalized leakage as defined by ASHRAE (See Standard 119, 1988), ELA is the Effective Leakage Area measured by methods such as ASTM E779 (2003) in the same units as the floor area ($FloorArea$) and N_{story} is the number of stories of the house.

Air tightness is a building property. The interaction of air tightness with external driving forces, most notably wind speed and temperature difference create infiltration (which in turn combine with mechanical systems to affect the total ventilation). To link NL (or any other air leakage metric) to the total ventilation we must use an infiltration model.

Infiltration Model

The LBL infiltration model, shown below, estimates flow through the building shell, Q, based on the leakage area of the shell (ELA), wind and stack factors (f_w f_s), and temperature difference (ΔT) and wind speed (v) at the house site.

2. $$Q = ELA \cdot s$$

where the specific infiltration (s) at any moment of time is given by:

3. $$s = \sqrt{f_s^{\,2} \cdot \Delta T + f_w^{\,2} \cdot v^2}$$

The details of the model can be further explored in, for example, Sherman and Matson (1997), but we will use the numerical values from ASHRAE Standard 119 (1988), which were based on combinations of presumed leakage distribution, wind pressure coefficients, terrain factors, etc.

4. f_s=0.12 m/s-$K^{1/2}$ (17.6 ft/min-$F^{1/2}$) and f_w=0.132 [-]

Infiltration and ventilation are often referred to in air changes per hour. To convert between the two it is necessary to use the volume of the space. The air change rate in air changes per hour (ACH) for a single story home due to infiltration can be found from the specific infiltration and normalized leakage as follows:

5. $$ACH_I = k_I NL \cdot s$$

where for unit conversion: k_I*=1.44 s/hr-m (0.0073 min/hr-ft)* assuming a normal single-story height. (This constant would otherwise decrease inversely proportional to the average story height.)

Ventilation Effectiveness

From the perspective of acceptable indoor air quality, the purpose of ventilation is to dilute the concentration of contaminants. We generally seek to control the average concentration of contaminants received over some period of interest. With constant emission strength and constant total ventilation this is a trivial calculation. Since pollutant concentration is non-linear with respect to ventilation rate, however, a simple average of the ventilation rate cannot be used, when the ventilation varies over time. Instead, the term effective ventilation is defined as the steady state ventilation that would yield the same average pollutant concentration over some time period as the actual time varying ventilation in that same time period.

ASHRAE Standard 136 (1993) was a first attempt to determine the contribution of infiltration towards providing ventilation. The algorithm used was based on approximations made by Yuill (1986) and used a variety of weather sources available at the time. The result was a table of "W" values that link the effective ventilation due to infiltration to the normalized leakage:

6. $$ACH_{eff} = NL \cdot W$$

Sherman and Wilson (1986) have further developed the approach of effective ventilation and we will use that definition herein to quantify the contributions of time varying ventilation. It is important to note that the contaminant source strength was assumed to be constant over the period of interest. This holds for many building contaminants where the source emission varies slowly with time or operates in a stepwise fashion, *and* is unaffected by ventilation rate. Some important exceptions are radon or formaldehyde, where the emission rate can be affected by the ventilation of the building in some circumstances. If such special cases are relevant, more detailed techniques may be required.

Effective ventilation is calculated by first calculating the inverse, the characteristic time (τ_e) for the pollutant concentration to reach steady state, which is given below.

7. $$\tau_{e,i} = \frac{1 - e^{-ACH_i \Delta t}}{ACH_i} + \tau_{e,i-1} \cdot e^{-ACH_i \Delta t}$$

The mean ventilation efficiency is a non-dimensional quantity which is defined as the ratio of the mean effective ventilation to the mean instantaneous ventilation. It is shown in terms of the characteristic time. The closer the actual ventilation rate is to steady state over the period of interest the higher the ventilation efficiency will be.

8. $$\varepsilon = \frac{1}{\overline{ACH} \cdot \overline{\tau_e}}$$

Where the overbars indicate an average over time. The effective ventilation for that period will be the average ventilation for that period multiplied by the mean (temporal) ventilation efficiency (sometimes called *efficacy*) for that period.

Exposure Period

The ventilation effectiveness derivation above requires that we take averages over some period of time of the quantities involved. Since we are doing this analysis using annual weather data the nominal time period to average over would be a year. This would be appropriate if the relationship between the impact of the contaminants only depended on the average concentration of the contaminants, but that may not always be the case. Therefore we need to determine the relevant *exposure period*.

Contaminants in the indoor environment may interact with the body in different ways, which means their relevant exposure metric can be quite different. For example, one way is when the risk of disease is related to the total dose—that is the integrated concentration over time. Many types of pollutants are assumed to behave this way such as carcinogens like Radon or volatile organic compounds like formaldehyde.

At the other end are contaminants for which the average concentration over a quite short period of time is important. For example, carbon monoxide (CO) poisoning occurs when elevated levels happen over the period of hours and total dose itself is unimportant.

Toxics such as chlorine gas may be intermediate where there is a non-linear relationship between exposure time, concentration and disease.

From our standpoint these issues can be handled by presuming there is a relevant *exposure period* for each contaminant of concern.

For those contaminants where dose is the key metric or where long-term averaging, the annual average is appropriate since the annual average represents the long term average there is only a single exposure period that needs to be analyzed.

For other contaminants one may wish to consider shorter exposure periods because of the chemistry of the contaminant. In such a case there will be many exposure periods in the analysis year. Thus it will important to determine the *critical exposure period* when doing the analysis.

Intermittency

The approach of using efficacy based on equivalent exposure is also used when treating the issue of intermittent ventilation, such as a fan that is on for some period of time and off for some period of time, on a regular schedule. Sherman (2006) has examined this problem from a theoretical standpoint, but such a treatment is not usable for infiltration because it does not follow any regular on/off pattern—but the net efficacy term can be used in the same way and so the same symbol is used for the various types of ventilation efficiency.

Infiltration Efficiency

Infiltration varies from hour to hour over the year. Indeed there may be times when infiltration may go to zero and no dilution will occur for that period. So to evaluate the net benefits of infiltration towards controlling indoor contaminants, we need to apply the (temporal) ventilation effectiveness concept to infiltration.

To do so requires the use of an infiltration model and typical weather data for an entire year. The former is described above and for the weather data we use the newly released TMY3 data files (NREL 2008).

We define infiltration efficiency as a special case of ventilation efficiency. Generalized ventilation efficiency as defined by Sherman and Wilson is based on the simple average over the time period in question. We are going to look at exposure periods anywhere from a day to a year. In order to compare the impacts of these different approaches they must all be relative to the same basis. So the reference for our infiltration efficiency will be the longest term (i.e. annual) average. So the effective ventilation becomes defined through the following expression:

9. $$ACH_{eff} = \varepsilon_I \cdot ACH_{I,annual} = \frac{1}{\tau_e}$$

where the average used for the characteristic time is for the relevant exposure period of the contaminant(s) of concern.

In principle we can use this to calculate the infiltration efficiency for any location in which we have annual weather data. There are, however, two additional parameters that must be determined before that can be done: air tightness and exposure duration.

Concentrations fluctuations are damped out by the volume of the indoor space and the air change rate. This effect was not included in the original Yuill approach, but is in the Sherman-Wilson approach. Thus there is some indirect dependency on the total ventilation rate and thus the air tightness.

To explore the size of that effect we will use two very different normalized leakage levels. Sherman and McWilliams (2007) and Sherman and Dickerhoff (1994) have shown that the stock of existing homes is quite leaky and we shall use a value of NL=1 to be typical of that data. On the other hand, new homes are substantially tighter (See for example Sherman and Matson 2002) and we shall use a value of NL=0.3 to represent those.

The second issue to address is one of relevant exposure time. That is, over what period of time do we wish to control the dose of contaminants? Standard 136 assumes that long-term (hence annual) exposure is relevant, but since other assumptions may be considered, we will calculate the infiltration efficiency for several exposure periods from one day to one year. For periods shorter than a year we will determine the result for the critical exposure period—i.e. the one that has the lowest efficiency.

Results

Table 1 contains the infiltration efficiency for six representative cities around the United States. These cities include mild, windy, cold, hot and humid combinations:

TABLE 1: Infiltration Efficiency , ε_I , for different time periods

CITY/STATE	NL	ACHannual	DAILY	WEEKLY	MONTHLY	ANNUAL	136
Long Beach,	0.3	0.21	66%	75%	81%	96%	89%
California	1	0.71	58%	69%	76%	92%	89%
Phoenix,	0.3	0.22	51%	60%	74%	94%	93%
Arizona	1	0.75	46%	58%	71%	90%	93%
Miami,	0.3	0.24	51%	66%	80%	90%	84%
Florida	1	0.8	41%	59%	71%	84%	84%
Chicago,	0.3	0.32	41%	56%	63%	90%	85%
Illinois	1	1.07	36%	52%	60%	87%	85%
Boston,	0.3	0.37	52%	60%	73%	92%	90%
Massachusetts	1	1.22	47%	58%	71%	91%	90%
Bethel,	0.3	0.43	48%	63%	68%	91%	88%
Alaska	1	1.42	45%	61%	67%	91%	88%

The first column of the table contains the city, the second is the normalized leakage used, the third is the annual average infiltration rate calculated from the TMY3 data. The next three columns represent the infiltration efficiency for the worst day, week and month respectively. The second to last column is the annual infiltration efficiency and the last column is our inference of what the infiltration efficiency is in standard 136. To get that we use the following equation

10. $$\varepsilon_{I,136} = W / k_I \cdot s_{annual}$$

where the "W" value is from ASHRAE Standard 136 and the "s" value is from Standard 119—which used the same basic weather data as each other[1]. These inferred values are listed for comparison purposes only. In general the 136-derived values correspond to the annual infiltration efficiencies as one would expect; they are, however, a few percent smaller overall.

We can extract some other trends from the data. First we can look at the impact that air tightness has on ventilation efficiency. For each climate we looked at two tightness levels which span a big range. For any given climate the impact of a tight vs. loose building envelope has only a very small effect on the temporal efficiency. Although the tightness, and hence infiltration, rates are over a factor of three different, the efficiencies change by only a few percentage points. The variations are biggest in the milder climates and when shorter time periods are being examined.

In general the infiltration efficiencies increase as the exposure period of concern increases. If long-term exposures are the appropriate measure than infiltration is roughly 90% effective at providing ventilation compared to a steady ventilation sources such a fan. By comparison, the efficiency on the worst day is roughly half of the annual efficiency—thus illustrating why it is important to determine the relevant exposure period for the contaminants one intends to control.

Sherman and McWilliams (2007) have calculated the average annual ventilation efficiency of infiltration on a county by county basis for the United States using air leakage and building specific information and different weather data. Their results are comparable to Table 1, but they have found a larger spread due to the larger number of sites considered and hence the geographical variation.

Impact of Mechanical Ventilation

The approach above can be used to find the effective ventilation due to infiltration, but due to infiltration alone. This may be quite appropriate when you have a leaky envelope and there is no need for mechanical ventilation, but when there is steady ventilation operating at the same time as infiltration the situation becomes more complex.

If we have mechanical ventilation operating on top of infiltration it is going to take away those periods of zero ventilation at the expense of raising the average ventilation—thus decreasing the variability that causes low efficiency. On the other hand, with a larger average ventilation rate, the system becomes a bit more sensitive to fluctuations (because the turn-over time is shorter)—thus amplifying variability. So, it is not clear what kind of changes to expect. Before we can examine the impacts further we must define infiltration efficiency in the context of combined mechanical ventilation and infiltration. To do that requires we will look at superposition.

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[1] For the 136 column only the data for San Diego was substituted for Long Beach because the Long Beach and Los Angeles data were inconsistent in standards 119 and 136

Superposition

"Superposition" is the term used to describe the combination of mechanical and natural ventilation. Sherman (1992) has examined the topic in some detail for a variety of cases. The simplest, most robust and one used by ASHRAE is to combine the unbalanced mechanical ventilation (such as a simple exhaust fan) in quadrature:

11. $$ACH_{total} = ACH_{bal} + \sqrt{ACH_{unbal}^{\ 2} + ACH_{I}^{2}}$$

This suggests that we should expand our definition of infiltration efficiency a bit to take into account the fact that the superposition of balanced and unbalanced flows is non-linear:

12. $$ACH_{eff} = ACH_{bal} + \sqrt{ACH_{unbal}^{\ 2} + \varepsilon_{I}^{2} \cdot ACH_{I,annual}^{2}}$$

These two expressions will be used in the sections below, but an alternative method not using these equations was considered and rejected. That method is summarized in the **APPENDIX: Integrating Superposition and Infiltration Efficiency**.

Balanced Ventilation

To see what impact the addition of some mechanical ventilation has, we redo the calculations of table 1 with the addition of 0.2 air changes of *balanced* mechanical ventilation. We chose 0.2 ACH because that is a typical value required by ASHRAE Standard 62.2 (2007). If we choose a much smaller value the results would be the same as in Table 1. If we choose a much larger mechanical ventilation value, the impact of infiltration would be small and therefore variations in its efficacy would not be very important.

TABLE 2: Infiltration Efficiency , ε_I , with 0.2 ACH Balanced Mechanical Ventilation

CITY/STATE	NL	ACH_{annual}	DAILY	WEEKLY	MONTHLY	ANNUAL
Long Beach,	0.3	0.41	63%	75%	81%	97%
California	1	0.91	60%	70%	77%	94%
Phoenix,	0.3	0.42	51%	60%	74%	94%
Arizona	1	0.95	46%	58%	72%	92%
Miami,	0.3	0.44	48%	65%	81%	93%
Florida	1	1.00	43%	60%	74%	87%
Chicago,	0.3	0.52	40%	58%	64%	93%
Illinois	1	1.27	36%	54%	61%	89%
Boston,	0.3	0.57	51%	60%	74%	95%
Massachusetts	1	1.42	48%	58%	72%	92%
Bethel,	0.3	0.63	46%	63%	68%	94%
Alaska	1	1.62	45%	62%	67%	92%

We can see in Table 1 that as expected the annual average air change rate is 0.2 ACH larger, but other than that there are no strong trends. The infiltration efficiencies change, but some go up and some go down compared with Table 1. There is a slight tendency for the values to go up and the variation between them to decrease.

Note that the "136" column is not included in this table, because there is no change in "W" described by the standard. Finally it is not clear that the differences between the values in Table 1 and Table 2 are significant, but they might be when a larger set of weather data is examined.

Unbalanced Mechanical Ventilation

The case above was analyzed assuming balanced mechanical ventilation such as that provided by an air-to-air heat exchanger (e.g. a Heat Recovery Ventilator). Unbalanced ventilation such as that provided by a continuously operating exhaust fan is also common. Unbalanced ventilation has different interactions with infiltration because unbalanced mechanical ventilation systems change the internal pressure of the house. Sherman (1992) has developed superposition equations to account for the addition of both balanced and unbalanced fans. These equations (which are embodied in Standard 136), are used to simulate the impact that a 0.2 ACH unbalanced fan would have on the infiltration efficiency.

Doing so provides a set of efficiencies very similar to that in Tables 1 and 2:

TABLE 3: Infiltration Efficiency , ε_I , with 0.2 ACH Balanced Mechanical Ventilation

CITY/STATE	NL	ACH_{annual}	DAILY	WEEKLY	MONTHLY	ANNUAL
Long Beach,	0.3	0.3	68%	80%	85%	99%
California	1	0.74	61%	71%	78%	94%
Phoenix,	0.3	0.31	54%	63%	78%	99%
Arizona	1	0.78	48%	59%	73%	92%
Miami,	0.3	0.32	52%	71%	86%	98%
Florida	1	0.83	46%	61%	75%	87%
Chicago,	0.3	0.38	43%	61%	67%	95%
Illinois	1	1.09	38%	54%	61%	88%
Boston,	0.3	0.42	53%	62%	76%	95%
Massachusetts	1	1.24	48%	58%	72%	91%
Bethel,	0.3	0.47	48%	64%	69%	94%
Alaska	1	1.44	45%	61%	67%	91%

The values in this table are quite similar to those in table 1. Thus using Equation 12 as our defining relationship for infiltration efficiency, allows us to estimate it once from weather data alone (i.e. Table 1) and then use it when combining it with steady forms of ventilation. This will on average slightly under-estimate the contribution of infiltration to effective ventilation but allows pre-calculation of the impact.

Intermittent Mechanical Ventilation

The above treatments assumed continuous mechanical ventilation combining with infiltration. Not all mechanical ventilation is continuous. Some is intermittent. Some is intermittent in the sense that it is cycled to provide an equivalent amount of continuous ventilation and some is intermittent in the sense that is may only be on for one hour every so often (e.g., to provide local bathroom exhaust.)

For any individual hour the mechanical ventilation adds as balanced or unbalanced flows to the infiltration using the equations above, but the question remains how to combine that over a longer term basis in which the infiltration is varying. We can break this question up into two regimes: correlated and uncorrelated.

If the mechanical ventilation is correlated with the infiltration the situation becomes more complex. This would be the case, for example, if a ventilation device were turned on when the infiltration was low but not when it was high. This would also be the case if the mechanical ventilation and infiltration both had strong seasonal trends In this case a full hour-by-hour simulation is necessary to determine the combined impact. This is not a difficult procedure to do, but there are far too many cases to consider to treat it in any generalized way. Additionally, this situation is not very common. We will not consider this case further herein.

More commonly intermittent mechanical ventilation is controlled either by a timer doing things in some regular manner (e.g. 20 minutes per hour, 20 hours on, 4 hours off; etc) or determined by specific activities that take place independent of infiltration rate (e.g., cooking, bathing, etc.). In this case the equivalent steady mechanical ventilation can be determined from the intermittent pattern and that equivalent steady mechanical ventilation can then be combined with infiltration as above.

The method of Sherman (2006) can be used to find the equivalent steady-state ventilation for a given pattern of intermittency. If we apply this method to typical spot exhaust fans in the 25-75 l/s (50-150 cfm) range, the efficacy is close to unity and we can take the simple daily average. If we consider large ventilation devices such as economizers or commercial sized kitchen exhaust, the efficacy can drop substantially and must be taken into account.

Impact on Residential Ventilation Standards

Infiltration operates in all homes. It exchanges air. This air impacts both energy costs and indoor contaminant levels. When writing residential ventilation standards it is important to decide how infiltration should be counted. It is also important to consider how it interacts with ventilation systems. (Russell et al (2005) have reviewed common ventilation systems.)

The current version of ASHRAE's residential ventilation standard 62.2 (2007) incorporates a fixed default amount of infiltration (about 2/3 of the average, to partially meet the ventilation requirements). Additionally, for existing buildings, measured infiltration above the default amount can be partially counted. While the current standard has some ambiguities in this process, it is an improvement on prior standards. The predecessor of 62.2 (62-99) allowed infiltration and natural ventilation to be used, without verification, to make up the entirety of the requirement.

Further improvements in this area of the standard are possible, but specific issues have to be considered before those improvements can be made:

Infiltration Air Quality

Air which enters the house for ventilation purposes should be free from any significant source of contamination or it is not suitable. The quality of infiltrating air can be poor if it comes from a contaminated space such as a garage—in which case infiltrating air should not be counted toward pollutant dilution/contaminant control. Standard 62.2 has such a provision already. Similarly air which is brought into building cavities where condensation can occur can cause failures.

The same issue, however, exists for exhaust ventilation systems. Such systems use an exhaust fan to depressurize the building and pull air in through the same leaks as infiltration uses. Anytime infiltration should not be used because of supply air quality concerns, exhaust ventilation should not be used.

Although not widely used in the United States, passive air inlets can be used either with natural or mechanical systems to provide uncontaminated outdoor air. These must be sited and sized properly to avoid pulling contaminated air through the leaks, but still provide sufficient ventilation.

Contaminants of Concern

Ventilation standards may not address individual contaminants, but in deriving minimum ventilation rates and other requirements, representative contaminants or contaminant classes must be considered. Quite generally minimum ventilation standards should look at commonly and reasonably occurring contaminants such as those from typical building materials and systems, occupant activities and consumer products.

For acute exposure to toxic compounds there can be 1-hr or 8-hr exposure limits. This is reasonably typical for an industrial environment, where processes and functions may require the use or generation of such toxins. In such cases it is important to know what the ventilation rate may be in the worst 1-hr or 8-hr period.

Generally residential ventilation standards are not designed to protect against acute exposures, but rather for long-term exposures; so that neither the sources strengths nor ventilation rates needs to be tracked over short periods. Many key contaminants, for example, are known to have seasonal variations in their emission rates because of changes in environmental conditions and seasonal usage patterns.

This suggests that the right averaging time is one year in order to capture all the important impacts. If averaging periods shorter than one year are deemed appropriate, however, then variations in sources need to be considered as well as variations in infiltration/ventilation. For a given concentration limit, shorter periods will tend to require higher overall ventilation rates.

Default Air Tightness

The calculation of infiltration efficiency depends slightly on the air tightness assumed for use in the simulation run. For a specific house that number is known, but in the general case we should use a reasonable default. The value NL=0.3 is a reasonable default because at that leakage level the infiltration is on the order of desired ventilation rate in ventilation standards such as ASHRAE 62.2. This will tend to slightly under-estimate the effective ventilation for very leaky homes. This is acceptable because it errs in a conservative direction, that is, undercounting infiltration contributions to contaminant dilution. Similarly, it will slightly over-estimate the impact in extremely tight homes, but that is moot since the contribution of infiltration will be so small.

Summary, Conclusions and Recommendations

The Sherman-Wilson approach was used to illustrate the effect of infiltration on indoor pollution dilution and determine the equivalent steady-state ventilation. This allows us to account for the effects of infiltration on pollutant dilution so as to minimize the mechanical ventilation requirements and therefore reduce energy use related to (over)ventilation.

An equation (Equation 12) can be used such that the same efficiency that describes the infiltration-only case can be reasonably used to describe the impact with combined infiltration and mechanical ventilation.

We have found that a key parameter is the relevant exposure period. Infiltration can be highly effective when long-term exposure is relevant, but can be substantially reduced when acute exposures are the over-riding concern.

A key conclusion is that when looking at the impacts of air tightness on mechanical ventilation, balanced and unbalanced systems behave very differently. That impact is in fact bigger than the impact that the time varying nature of infiltration has itself. Thus in any real house balanced and unbalanced systems must be treated differently to account for the air tightness impacts.

ASHRAE Standard 136

ASHRAE Standard 136 needs to be revised to incorporate improved and expanded weather data and to use the technically superior approach of the Sherman-Wilson model. In doing so certain decisions need to be made regarding default conditions (e.g. air tightness) and exposure duration.

The standard should be expanded to include the infiltration efficiency as defined herein. This should be in addition to the "W" factor.

The superposition description should be improved to reflect the results presented above.

Standard 136 should be coordinated with Standard 62.2 on issues such as exposure period and mechanical ventilation defaults.

In addition the approach of using W (e.g. Equation 6) to determine air change rate is based on the assumption of a standard ceiling height for the space and thus does not include ceiling height as a variable. It predicts that the air change rate would be independent of ceiling height for a given normalized leakage. That leads to a significant over-prediction of air flow for houses with large areas cathedral ceilings, atria or other kinds of high ceilings. This problem can be easily fixed, but is in fact moot if one goes to an infiltration efficiency approach instead of using W factors.

ASHRAE Standard 62.2

Standard 62.2 needs to be revised to properly account for infiltration. This revision can be done with the results presented herein, but certain decisions have to be made before that can be done:

- Is air that comes through cracks, penetrations and other adventitious openings of equivalent quality for dilution purposes as air ducted from outside. If it is not, then infiltration and all exhaust ventilation must be discounted.
- Should energy concerns be included as part of the 62.2 requirements or considerations. If so, then infiltration must be discounted appropriately because of its general increase during peak heating and cooling conditions and mechanical ventilation systems must be discounted based on the electrical energy required to move the air. Heat recovery ventilation systems (passive or active) must be given appropriate credit. If not, then requirements should be based on the ability of different systems to provide appropriate dilution
- What are the relevant exposure periods for the key contaminants of concern? The current standards 136 and 62.2 assume that annual average exposure is an appropriate criterion. If that is not the case then Standard 136 needs to be recalculated for shorter time periods and source strength variations need to be considered in 62.2. (If very short periods are deemed appropriate then the intermittent ventilation approach in 62.2 needs to be revised as well.)

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APPENDIX: Integrating Superposition and Infiltration Efficiency

The definition of infiltration efficiency in the text uses an explicit algorithm for superposition. It is possible to avoid doing that by integrating the effects of superposition and infiltration efficiency together. To do so, we define infiltration efficiency as follows:

13. $$ACH_{eff} = ACH_{fan} + \varepsilon_I \cdot ACH_{I,annual}$$

where ACH_{fan} is the air change rate assumed to be from steady mechanical ventilation system.

For the case of balanced ventilation this is exactly that same as that in Table 2, as both definitions reduce to the same formulate, but for unbalanced ventilation they are different.

Unbalanced Mechanical Ventilation

Unbalanced ventilation has different interactions with infiltration, because unbalanced mechanical ventilation systems change the internal pressure of the house. In the main text this is handled using the superposition equation. Using this appendix's definition of infiltration efficiency for the same situation as that of Table 3, the efficiencies are must lower because they include the effect of superposition inherently:

TABLE A1: Efficiency of Infiltration with 0.2 ACH Unbalanced Mechanical Ventilation

CITY/STATE	NL	ACH_{annual}	DAILY	WEEKLY	MONTHLY	ANNUAL	SUPER
Long Beach,	0.3	0.30	22%	29%	33%	43%	48%
California	1	0.74	39%	48%	54%	69%	76%
Phoenix,	0.3	0.31	15%	20%	29%	44%	50%
Arizona	1	0.78	28%	38%	51%	69%	77%
Miami,	0.3	0.32	15%	26%	36%	45%	50%
Florida	1	0.83	28%	41%	54%	65%	79%
Chicago,	0.3	0.38	14%	25%	29%	51%	56%
Illinois	1	1.09	24%	39%	45%	72%	83%
Boston,	0.3	0.42	21%	28%	39%	55%	59%
Massachusetts	1	1.24	34%	44%	57%	76%	85%
Bethel,	0.3	0.47	20%	33%	37%	58%	63%
Alaska	1	1.44	33%	49%	54%	78%	87%

We see from Table A1 that the efficiencies for all time regimes have been significantly reduced compared to the balanced fan case. A comparison between the average annual air change rates shows that the primary reason for this decrease is because unbalanced fan are assumed to add in quadrature rather than linearly on a moment by moment basis.

Comparing Table 3 and Table A1 shows that unbalanced fans are less efficient than balanced fans when combined with infiltration. It is not, however, clear that this metric is of general value as it will be quite dependent on the relative sizes of mechanical and natural ventilation.